Space geodetic constraints on fault slip rates and the distribution of aseismic slip on Bay Area faults

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Annual Project Summary for FY2005 Activities

This report provides an update of our geodetic investigations in the San Francisco Bay area to constrain fault slip rates and the distribution of aseismic slip. The research is relying on the collection and analysis of space geodetic data (GPS and InSAR) for fault-slip information, and modeling and interpretation of those results in the context of fault slip rates, the locked or aseismically creeping nature of individual segments of the southern Bay area fault system, and earthquake potential from those faults. Significant portions of this work have been published in 2005 (d'Alessio et al. 2005; Johanson and Bürgmann, 2005; Schmidt et al., 2005).

1. Investigations Undertaken

The San Francisco Bay Area is a structurally complex region of the North American-Pacific plate boundary. We yearly occupy an extensive Global Positioning System (GPS) network in the Bay area and also incorporate data collected by the USGS. In the last two years, we have extended the network further into the creeping section of the SAF. The BAVU (d'Alessio et al., 2005) velocity-field product documents the results of this analysis, including coordinate time series, station velocities and other information of use to others interested in studying the active deformation of the region, http://seismo.berkeley.edu/~burgmann/RESEARCH/BAVU/index.html.

The GPS data are integrated with other data sets such as the creepmeter records on the Hayward, Calaveras and San Andreas faults (Data collected by USGS, SFSU and CU Boulder). Although the use of InSAR in the southern Bay Area has been challenged by large amounts of decorrelation noise, it has become a feasible data source through our implementation of a statistical-cost network-flow unwrapping algorithm and a novel data stacking approach (Johanson and Bürgmann, 2005). We are also incorporating subsurface slip rates on creeping members of the SAF system using repeating micro-earthquakes (e.g., Schmidt et al., 2005).

This report will focus on three aspects of this investigation:

- A brief update on the regional deformation field in the San Francisco Bay Area (d'Alessio et al., 2005) and our attempt to obtain reliable vertical site velocities from the GPS data analysis.
- Preliminary results based on the use of a new comprehensive PS-InSAR data set towards improved analysis of the Hayward fault locking patterns (Funning et al., 2005).
- The inversion of GPS and InSAR data to detect and characterize the distribution of aseismic slip on the San Juan Bautista segment of the San Andreas fault fault (Johanson and Bürgmann, 2005).
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2. Results

GPS velocities in the Bay Area

In an effort to put together the most comprehensive picture of crustal deformation in the San Francisco Bay Area, we developed the Bay Area Velocity Unification (BAVU, "Bay View") crustal motion product (D'Alessio et al., 2005). This compilation includes survey-mode GPS data from nearly 200 GPS stations throughout the greater San Francisco Bay Area from Sacramento to San Luis Obispo collected from 1991 to 2004 by U. C. Berkeley, the U.S. Geological Survey, the California Department of Transportation, Stanford University, U. C. Davis and the Geophysical Institute in Fairbanks, AK. These are combined with continuous GPS data from the Bay Area Regional Deformation (BARD) network. We process the GPS data using the GAMIT/GLOBK software package. For a given day, we include data processed locally as well as solutions for the full IGS and BARD networks processed by and obtained from SOPAC at the University of California, San Diego. The daily combined solutions are merged into monthly averaged solutions for time series and velocity estimation. BAVU provides a consistent velocity field for monitoring fault slip and strain accumulation throughout the greater San Francisco Bay region. A detailed discussion of the BAVU results and block modeling of the regional deformation has been published (d'Alessio et al., 2005). Figure 1 shows a closeup of the GPS residual velocities after subtracting an interseismic elastic strain accumulation model from the BAVU dataset in the south Bay area near the epicentral region of the 1989 M_w 6.9 Loma Prieta earthquake. Vertical rates are shown for sites for which the formal uncertainty has been determined to be < 2 mm/yr. Also shown are residuals of the PS-InSAR data in the region. We note that the epicentral region appears to undergo right-lateral shear, overall contraction and subsidence during the 1992-2000 time interval. We are currently investigating this deformation pattern in the context of enduring postseismic viscous relaxation following the 1989 earthquake.

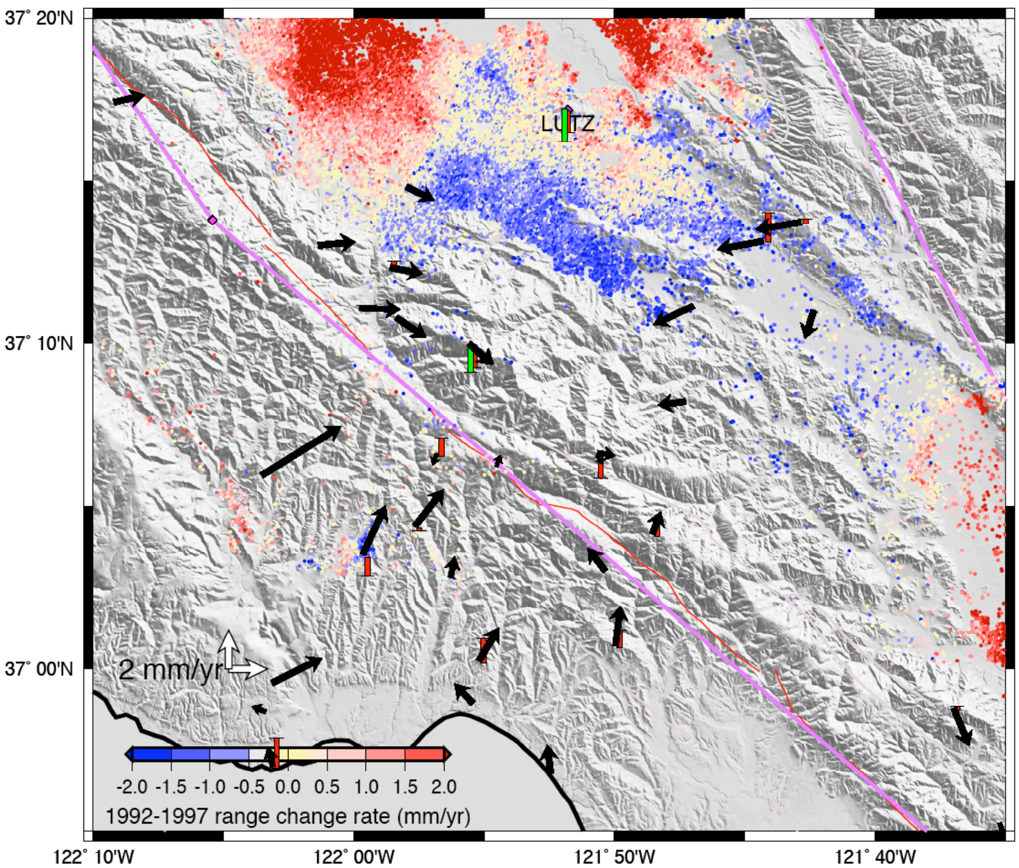


Figure 1. Difference between observed GPS velocities and model calculations in the epicentral region of the Loma Prieta earthquake. Vertical GPS rates are shown for sites with formal V_{up} uncertainties < 2 mm/yr) in the BAVU solution (red bars) and from the SOPAC solution for BARD CGPS sites (green bars).

Aseismic slip along the Hayward fault

Schmidt et al. (2005) solve for the slip-rate distribution on the Hayward fault by performing a least-squares inversion of geodetic and seismic data sets. InSAR data from 13 independent ERS interferograms are stacked to obtain range-change rates from 1992 to 2000. Horizontal surface velocities of a subset of 141 BAVU sites are measured using GPS from 1994 to 2003. Surface creep observations and estimates of deep slip rates determined from characteristic repeating earthquake sequences are also incorporated in the inversion. The inferred slip-rate distribution is consistent with a fault that creeps aseismically at a rate of ~5 mm/yr to a depth of 4 to 6 km; a low slip-rate patch of less than 1 mm/yr is inferred beneath San Leandro (Schmidt et al., 2005). The results suggest that the Hayward fault is currently accumulating a slip rate deficit equivalent to a $\mathbf{M}_w = 6.78 \pm 0.05$ event per century.

We are now working on utilizing a much expanded and comprehensive InSAR data set, processed using the permanent scatterer analysis method of Ferretti et al. (2000, 2001). See annual report 05-HQGR-0038 (Active Uplift and Thrust-fault Strain Accumulation Rates from PS-InSAR and GPS data), Ferretti et al. (2004); Hilley et al. (2004); and Bürgmann et al. (2005, in press), for more information on this approach and results from our related investigations. This analysis currently incorporates information from 49 acquisitions of the ESA ERS-1 & 2 spacecraft from 1992-2000. We have also begun integrating data from >30 acquisitions of the RADARSAT satellite, which provides a complementary viewing geometry (ascending vs. descending orbit tracks) and time span (2001-2004). Figure 2 shows the sub-sampled observed, modeled and residual range-change rates of both ERS and RADARSAT data sets and GPS-measured horizontal velocities. One great advantage of the PS-InSAR approach is that we now have significant amounts of data from the highly vegetated region of the East Bay Hills to the east of the Hayward fault, where previously no information could be obtained from standard InSAR analysis due to loss of phase coherence. The model includes deep-seated strain accumulation below major strike-slip faults and a more complex distributed-slip model along the Hayward fault shown in Figure 3. In this preliminary analysis of the data, Funning et al. (2005) find that the overall pattern of aseismic slip derived from these new data sets is consistent with that obtained by Schmidt et al. (2005).

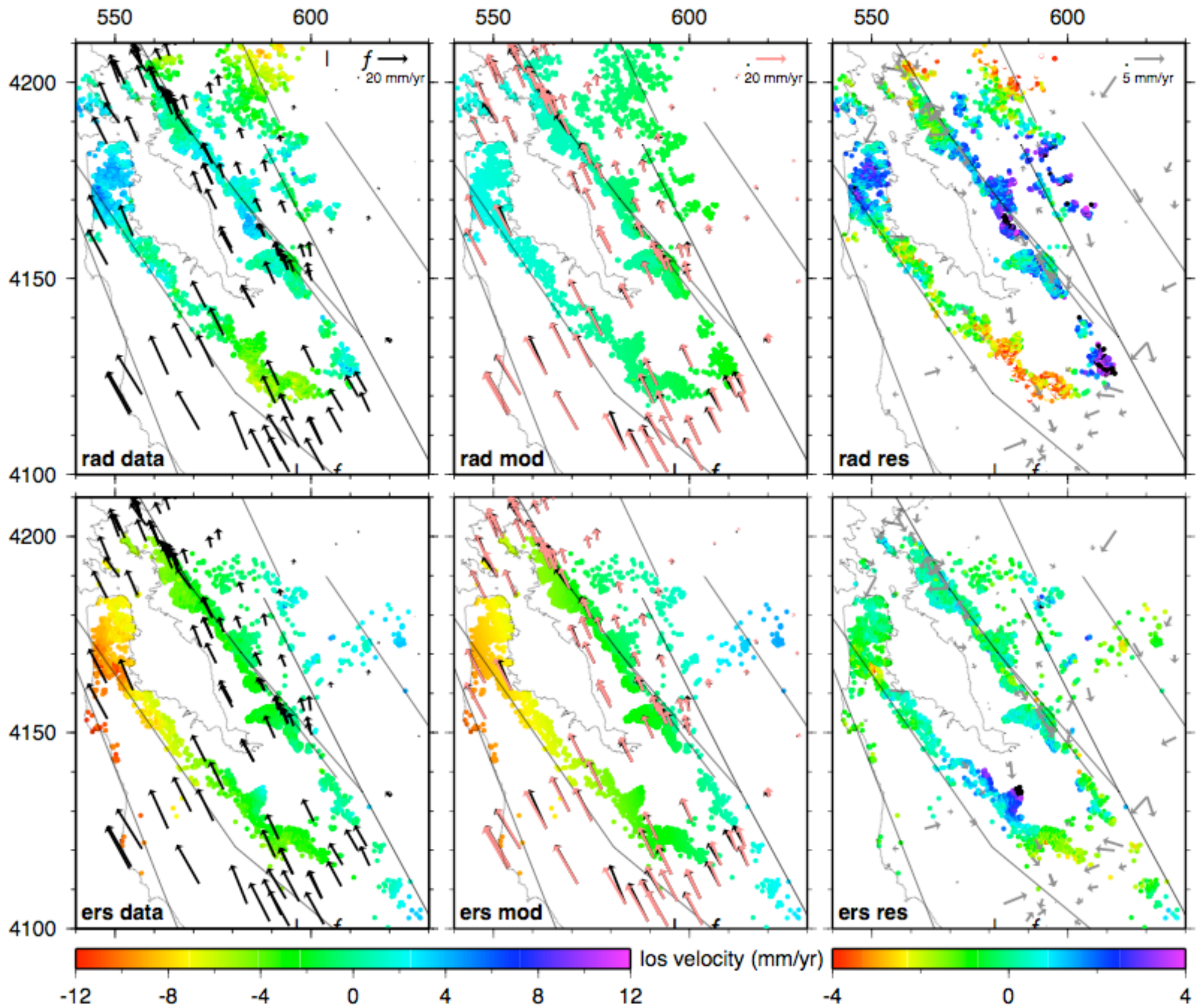


Figure 2. Observed (left column), modeled (middle) and residual (right) GPS velocities (arrows) and PS-InSAR-measured range change rates (color circles). Top row shows sub-sampled PS-rates from the ascending RADARSAT, the bottom row rates from the descending ERS-1&2 acquisitions. The interseismic model includes regional deformation from deep dislocation below the San Andreas, Hayward, Calaveras and Greenville-Green Valley faults (surface projection shown as black lines), and the distributed slip model from the joint inversion shown in Figure 3 (Funning et al., 2005).

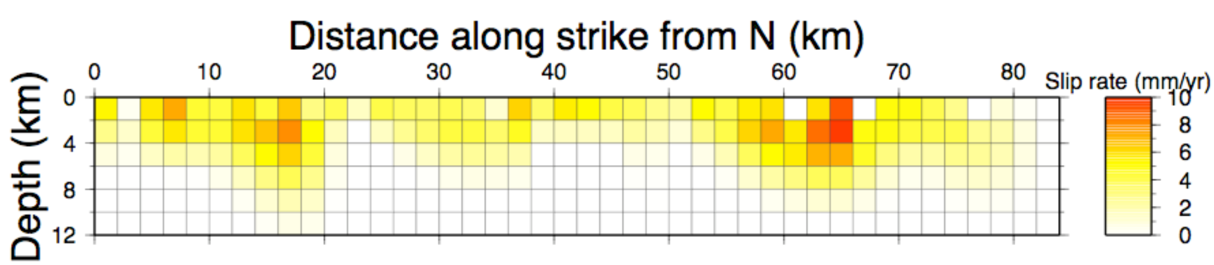
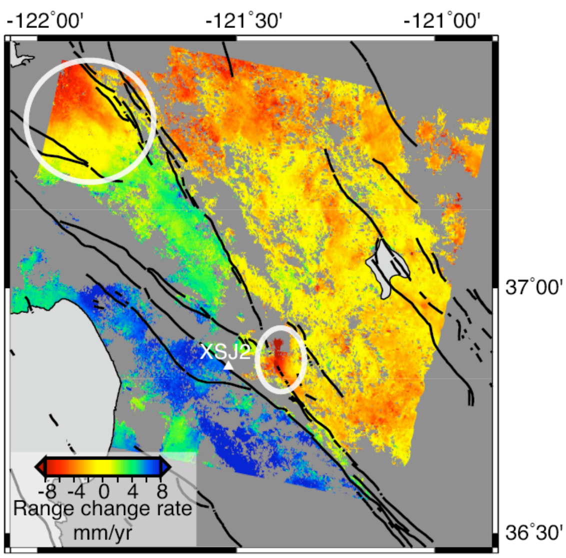


Figure 3. NW-SE section along the Hayward and Mission faults of a preliminary distributed strike-slip inversion of regional GPS data and PS-InSAR range-change data collected by the ERS-1&2 and RADARSAT spacecraft (from Funning et al., 2005). The slip pattern is mostly consistent with the results of Schmidt et al. (2005), which relied on a stack of 13 ERS interferograms, surface creep rates and subsurface repeating earthquake data.

Creep and locking on the San Andreas fault near San Juan Bautista

The San Juan Bautista segment forms the northern transition zone of the creeping section of the San Andreas fault. It is an area of moderate seismicity; the largest instrumentally-recorded earthquakes have been M 5.5. However, historic records suggest six M ≈ 6 earthquakes occurred near the segment between 1840 and 1899. It is also an area that has experienced several slow earthquakes. Johanson and Bürgmann (2005) perform a joint inversion of GPS and InSAR data to determine the current rate and distribution of interseismic creep on the San Andreas fault and deep, interseismic slip rates along the major strike-slip faults in the Bay Area (Figure 4). We find two low-slip/locked segments at mid-seismogenic depths that may represent source regions for the 19th century earthquakes (Figure 4B). The results suggest that the San Juan Bautista segment is currently accumulating strain energy at the rate of one M 6.3 – 6.7 earthquake per century.



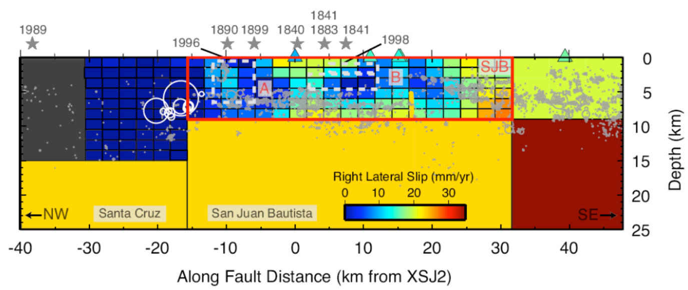


Figure 4. (A) InSAR stack from data spanning 5.75 years, scaled to yearly rate. White circles outline the Hollister and Santa Clara Valley Basins where groundwater recharge results in non-tectonic uplift. These and other areas located on Quaternary sediment were removed before the model inversion. White triangle is the location of creepmeter XSJ2, used as the origin for the slip distributed model in (B).

(B) Results of model inversion for the San Juan Bautista segment from BAVU-GPS velocities and InSAR data. Cross-section is plotted looking north-eastward. Surface creep rates from line fits to creepmeter data from 1994 – 2001 are shown for comparison (colored triangles). The rupture areas for slow earthquakes in 1996 and 1998 are outlined in dashed grey lines (Gwyther et al., 2000). Red outline is the shallow SJB segment used to calculate moment deficit. Letters indicate asperities A & B. Grey circles are micro-earthquakes, white circles 20 km north of XSJ2 are the 1990 Chittenden swarm, the white circle 10 km south of XSJ2 is the 1998 Mw5.1 San Juan Bautista earthquake. Grey stars are the projected locations of M 6 earthquakes within 5 km of the San Andreas fault surface trace from Toppozada et al. (2002). Black area signifies that no slip rate was estimated for that fault region.

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3. Non-technical Summary

We use the Global Positioning System (GPS) and Synthetic Aperture Radar Interferometry (InSAR) to gather information on crustal deformation and earthquake hazard along the major strike-slip faults in the San Francisco Bay region. GPS and a new permanent scatterer InSAR data set about the Hayward fault are utilized to determine a detailed model of the distribution of locked and aseismically creeping portions of the fault in the subsurface. Despite significant creep on the fault in the upper 6 km, a slip deficit rate corresponding to as much as one M ≤ 7 per century is found. A similar analysis of the San Andreas fault near San Juan Bautista finds significant locked fault patches in this transition region of locked-to-creeping behavior. Thus, several M≈6 in the last century are likely to have orginated along this fault segment.

4. Reports Published (2004 – 2005)

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Toppozada, T. R., D. M. Branum, M. S. Reichle, and C. L. Hallstrom (2002), San Andreas fault zone, California: M ≥ 5.5 earthquake history, Bull. Seism. Soc. Am., 92, 2555-2601.

6. Data Availability

Time series, velocities and other data documenting the BAVU velocity field are available via: http://seismo.berkeley.edu/~burgmann/RESEARCH/BAVU/index.html

GPS Processing

- Processing Methodology
- GAMIT files
- Timeseries

Maps

- Global Stations
- California Stations
- Bay Area
- Hayward fault

Papers and Presentations

- JGR Manuscript (please email for a preprint)

.....Supplementary Tables

- AGU 2005 Spring Meeting Powerpoint File
- AGU 2004 Fall Meeting * Powerpoint File

(*AGU Outstanding student paper award)

Download DATA Products

- Download Final Velocity Field

Raw and RINEX formatted GPS data files for static surveys of markers in the San Francisco Bay area from 1994-2004. These files typically include greater than six continuous hours of data, recorded at a 30 s collection rate with a 10-degree elevation mask. These data are freely available through the UNAVCO archive facility in Boulder, and also at the University of California, Berkeley. http://archive.unavco.ucar.edu/cgi-bin/dmg/groups?cpn=1&oby=group_name
Data collected by our group for this project are archived under the Group Names of “Calaveras Fault”, “Hayward Fault” and “Loma Prieta.”

Photocopies of survey log sheets and site descriptions are also available. Additional data used in this study included RINEX format files obtained from the U.S. Geological Survey and the Bay Area Regional Deformation Network (BARD). These files include campaign-style surveying (USGS) and continuous GPS stations (BARD) and are available at the NCEDC at UC Berkeley.

InSAR data used in this project are available via the WInSAR archive, supported in part by the USGS.

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